

Modeling Of Physiological Characteristics of Leaves Pine Trees for Estimate Current Annual Increment Growth in Northern Iraq

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Annotation: Physiological processes occurring within tree leaves influence key leaf characteristics, which, in turn, impact overall tree growth. Incorporating these physiological traits into mathematical models enhances their predictive accuracy, particularly when estimating vegetation dynamics. In this study, random samples were collected from pine trees at the Dohuk site, comprising 13 samples with five trees per sample. Phenotypic and physiological attributes of the leaves were measured, including diameter at breast height (DBH), total tree height, and the number of branches per tree. Additional estimates included basal area, crown coverage area, crown length ratio, relative crown length, diameter growth, annual height increment, annual volume growth, leaf surface area, leaf thickness, and nutrient composition. The carbon-to-nitrogen ratio and chemical content of the leaves were also analyzed. Statistical analysis was performed to determine the correlation between essential nutrients (nitrogen, phosphorus, potassium, calcium, magnesium), carbohydrates, and carbon with the annual growth parameters of the trees. The results, visualized using a heat map of the correlation matrix, revealed significant color variations corresponding to correlation values. Findings indicated that annual diameter growth in pine trees significantly affects leaf thickness and mass per unit area, with a coefficient of

determination (R^2) of 84.57% and a standard error of 0.00212. These results suggest the reliability of this model for growth estimation. Moreover, current annual growth rates in height and volume for *Pinus brutia* exhibited strong correlations with magnesium and carbon levels. Multiple regression analysis yielded determination coefficients of 95.31% for height and 97.85% for volume, with corresponding standard errors of 0.01038 and 0.000914. Residual analysis confirmed the robustness of these models, making them dependable tools for estimating current annual growth in height and volume of naturally regenerating *Pinus brutia* in northern Iraq.

Keywords: growth functions, pine trees, current annual increase, multiple regression models.

Introduction

The crown canopy of a tree, comprising its leaves, serves as the primary site for physiological processes vital to the tree's growth and development. Accurately determining the leaf surface area and monitoring the tree's vitality are essential, as these factors directly influence growth, development, and long-term sustainability. When multiple trees grow in a given location, their crown canopies form a collective structure that creates a microclimate influenced by canopy density. These variations in density lead to differences in growth and productivity, making the measurement of crown canopy surface area a critical task for forest managers. One effective technique for assessing crown canopy changes involves developing growth models linked to physiological characteristics. Such models are instrumental in understanding and predicting tree growth behavior. By simulating interactions between climate and vegetation, these models reflect the physiological processes occurring within the plant, especially in the leaves that form the crown canopy at the individual tree level (Prentice et al., 1992)(Younis. et al., 1992) Physiological interactions within leaves can result in growth variations, causing differences in the growth patterns of individual trees within the arboretum (Ali & Al-Yousif 2023) (Wullschleger et al., 2014). Wright et al. (2004) and Reich et al. (1999) highlighted that the amount of light received by leaves and the efficiency of its utilization are primarily determined by crown and leaf characteristics. Growth rates among tree species are influenced by variations in these characteristics; larger crown dimensions typically stimulate higher growth rates depending on the species. Modeling growth and productivity in forests plays a crucial role in managing natural resources. Such models contribute to achieving sustainability by supporting the environmental, social, and economic services provided by forests. They are used to analyze and predict how forest trees develop over time under the influence of various biotic and abiotic factors. These insights enable forest managers to forecast future growth and production, implement optimal management practices, and evaluate the impact of developmental interventions, such as thinning, on forest ecosystem dynamics. Moreover, growth models support the enhancement of forest vitality and the preservation of biodiversity and growing reserves, thereby ensuring forest sustainability (Peng, 2000). In light of these considerations, the present study aims to develop models that estimate current annual growth based on the physiological characteristics of trees.

Materials and Methods

The study was conducted in Dohuk Governorate, located in northern Iraq. The area lies between

latitudes 36°18'12.64" and 37°20'33.55", and longitudes 42°20'25.36" and 44°17'40.50", with altitudes ranging from 430 to 2500 meters above sea level. The region's climate resembles that of the Mediterranean basin, characterized by low winter temperatures, annual rainfall ranging between 600 and 800 mm, and hot, dry summers with high temperatures (Mzuri et al., 2021)(Mohammed et al., 2024). Sampling was performed at four randomly selected sites—Zawita, Atrush, Sierra Tica, and Achua—following preliminary surveys of the Dohuk Governorate. Thirteen circular plots, each with a radius of 17.9 meters, were established (West, 2015). The geographical coordinates for each plot's center were recorded, with the center point represented by a dominant tree, designated as the subject tree within the plot. Field measurements included the geographical coordinates, total tree height (meters), height to the crown center (meters), tree diameter at breast height (centimeters), crown diameter (meters), and the number of branches per tree. Additional estimates included basal area (m²), crown coverage area (m²), crown length (meters), crown length percentage, crown ratio, relative crown length, annual diameter growth, leaf surface area (cm²), and leaf thickness (mm). Nutrient and chemical content in the leaves, along with the carbon-to-nitrogen ratio, were also analyzed. Statistical analyses were conducted using a range of techniques to interpret and present the results. The analyses included traditional statistics, such as the coefficient of determination (R²), standard error, and residual analysis. These statistical measures were essential for evaluating the accuracy of the regression models and determining their suitability for the data. Residual analysis focused on examining the deviations between observed and estimated values, with residuals assumed to follow a normal distribution around zero. A normal distribution of residuals indicates an appropriate model with evenly distributed errors. Additionally, the absence of correlations among residuals suggests that the errors are random and uncorrelated. Conversely, patterns in residual distribution may signal that the model does not accurately represent the data (Smith, 2024).

Results and Discussion

Pinus brutia Ten trees exhibit distinct physiological characteristics that enable them to adapt and grow dynamically in northern Iraq. Understanding the relationship between these trees and both biotic and abiotic factors requires analyzing the connection between current annual growth functions—diameter, height, and volume—and physiological characteristics such as nitrogen, phosphorus, potassium, calcium, magnesium, carbohydrates, and carbon. A heat map of the correlation matrix was utilized to determine these relationships. The heat map displays color variations representing correlation values between growth function variables and physiological characteristics. The closer the correlation value is to -1, the darker the shade of blue, indicating a strong negative relationship between the variables. This visualization helps identify which physiological variables most significantly influence the annual growth functions of these trees, providing essential insights for developing mathematical models that predict and estimate growth patterns. For this analysis, data were collected from naturally growing *Pinus brutia* trees in the forests of Dohuk. The Statgraphics Version 18 program was used to conduct the correlation analysis between growth functions and physiological characteristics. The results are illustrated in Figure 1, showcasing the relationships and highlighting the physiological factors with the greatest impact on annual growth functions.

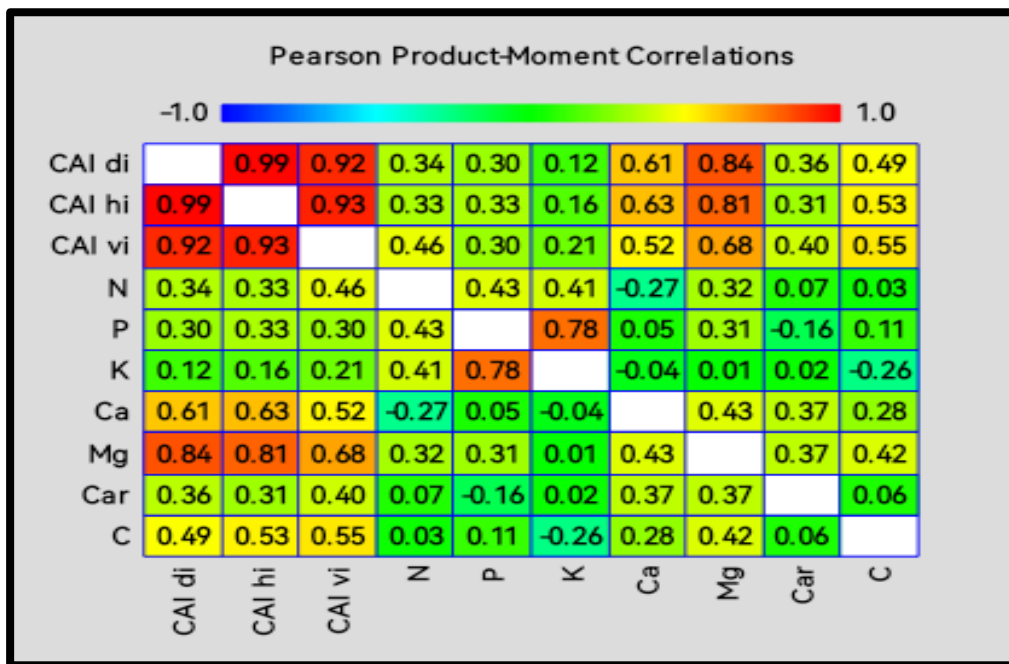


Figure (1): Thermal correlation matrix of growth functions with physiological variables of *Pinus brutia* trees

Figure (1) illustrates the varying correlations between growth functions and the physiological variables of *Pinus brutia* trees. Notably, there was a positive correlation between the current annual growth in diameter, height, and volume with calcium content, with correlation values of 0.61, 0.63, and 0.52, respectively. The significant role of calcium in enhancing physiological processes within plants (Bhardwaj & Sharma, 2017) and facilitating the transport of water and nutrients likely accounts for these findings.

Table (1) further shows that current annual growth in diameter, height, and volume also correlates positively with magnesium levels, with correlation values of 0.84, 0.81, and 0.68, respectively. Magnesium's role in chlorophyll synthesis, which promotes photosynthesis and subsequently supports tree growth (Marschner, 2012), explains this relationship. Additionally, Figure (1) reveals a positive correlation between the current annual growth in diameter, height, and volume and the carbon content of leaves, with correlation values of 0.49, 0.53, and 0.55, respectively. These findings align with current annual growth models for diameter, height, and volume, as described by (Gratani 2014). The estimation of current annual growth functions (diameter, height, and volume) plays a crucial role in administrative and developmental decision-making processes aimed at ensuring the sustainability of these trees. These estimations facilitate the assessment of different growth stages, enable the monitoring of annual changes, and help determine interrelationships between trees of the same or different species. Understanding these relationships supports informed decisions regarding silvicultural operations designed to enhance tree performance. Using the collected data and the Statgraphics program, various regression methods were applied to develop multiple equations linking current annual growth functions with physiological variables. These equations are summarized in Table (2), providing essential insights for forest management and sustainability planning.

Table (2) Equations for estimating the current annual Increment in (diameter, height, volume) of *Pinus brutia* trees

No.	Model	R ²	S.E.	DW
1	CAI d = 0.314182 + 0.00576071* Ca - 0.0382123 * Mg	82.35	0.00275	1.70
2	CAI d = 0.324941 - 0.0902817 * Mg + 0.00135837 * C	84.03	0.00216	2.03

3	$CAI d = 0.326148 - 0.000750957 * Car + 0.00546128 * Ca - 0.0370514 * Mg$	85.09	0.00223	1.80
4	$CAI d = 0.293596 + 0.203665 * Thick + 0.0350363 * LMA$	84.57	0.00212	1.88
5	$CAI h = 0.323802 - 0.515011 * Mg + 0.0111023 * C$	95.31	0.01038	1.70
6	$CAI h = 0.303421 + 0.0359911 * Ca - 0.427121 * Mg$	87.52	0.01847	1.27
7	$CAI h = 0.309089 + 0.0408458 * Ca - 0.44937 * Mg - 0.000526694 * Car$	90.62	0.01754	1.58
8	$CAI h = 0.000193551 + 4.24187 * Thick + 0.0547957 * LMA$	75.46	0.03255	1.43
9	$CAI v = 0.0262786 - 0.0674502 * Mg + 0.00151081 * C$	97.85	0.000914	1.75
10	$CAI v = 0.0214066 + 0.00456551 * Ca - 0.0451696 * Mg$	88.60	0.00199	1.40
11	$CAI v = 0.0273687 + 0.00441437 * Ca - 0.0450945 * Mg - 0.000407368 * Car$	93.27	0.00145	1.77
12	$CAI v = -0.0130238 + 0.518713 * Thick + 0.0013031 * LMA$	93.76	0.00164	1.71

From observing Table (2), it is evident that the growth functions of *Pinus brutia* trees can be estimated based on various physiological variables, including the nutritional content of the leaves and leaf characteristics such as thickness and leaf mass per unit area. According to equations (1, 2, 3, and 4), which estimate the current annual growth in diameter (CAI d) of pine trees, the coefficient of determination (R^2) values were found to be 82.35, 84.03, 85.09, and 82.57, respectively. The corresponding standard errors were 0.00275, 0.00216, 0.00223, and 0.00272, respectively, while the Durbin-Watson (DW) statistics were 1.70, 2.03, 1.80, and 1.88, respectively. These measurements indicate that all the listed equations are reliable for estimating the current annual growth of unequal-aged *Pinus brutia* trees, with equation (4) being particularly noteworthy due to its favorable statistical parameters.

CAI d = 0.293596 + 0.203665 * Thick + 0.0350363 * LMA

The current annual growth in the diameter of *Pinus brutia* trees was estimated based on two independent variables: leaf thickness and leaf mass per unit area, which were considered in multiple linear equations. Upon examining the statistical measures of the equation, it was found to be a good fit, with a coefficient of determination (R^2) of 84.57%. The standard error of the mean was 0.00212, and the Durbin-Watson (DW) statistic was 1.88, indicating the presence of a correlation between the variables. Both leaf thickness and leaf mass per unit area were found to significantly affect the estimation of current annual growth in diameter. To ensure the validity of the equation and confirm the absence of autocorrelation in the random errors of the independent variables, a residual analysis was conducted. It was observed that the residuals were randomly distributed around zero, indicating that the model is appropriate and that there were no discernible patterns in the points. This suggests that there is no autocorrelation between the observations. Consequently, the distribution is random, which enhances the model's predictive ability and confirms that there are no significant deviations from the expected value. The equation can be used to estimate the current annual growth in diameter of *Pinus brutia* trees of varying ages, and a graph was prepared as shown in Figure (2).

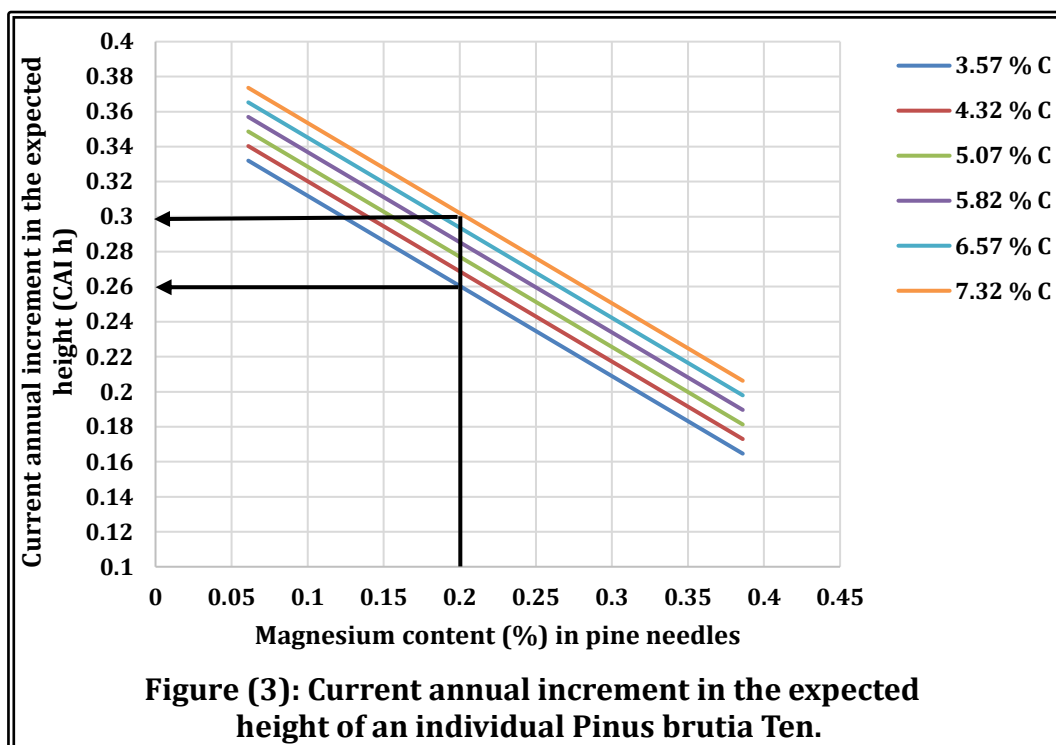
From Figure (2), it is evident that an increase in leaf thickness and leaf mass per unit area (LMA) of *Pinus brutia* trees results in a higher current annual growth in diameter. When the leaf mass per unit area is 0.3 kg per square meter and the average leaf thickness is 0.047 mm, the current annual growth in diameter is 0.314 cm. When the leaf thickness increases to 0.097 mm, with the

same leaf mass per unit area, the current annual growth in diameter is expected to rise to 0.324 cm.

Referring to Table (2), we observe that the rates numbered (5, 6, 7, 8) are used to estimate the current annual growth rate in height (CAI h) of *Pinus brutia* trees. The statistical measures for these equations, represented by the coefficient of determination (R^2), are 95.31, 87.52, 90.62, and 75.46, respectively. The standard errors are 0.01038, 0.01847, 0.01754, and 0.03255, respectively, and the Durbin-Watson (DW) statistics are 1.70, 1.27, 1.58, and 1.43, respectively. From this, we conclude that all of these equations provide reliable estimates and can be trusted for predicting current annual growth. We find that equation (5) is particularly effective.

$$C.A.I_h = 0.323802 - 0.515011 * Mg + 0.0111023 * C$$

Equation (5) has the highest coefficient of determination (R^2), reaching 95.31, which indicates a strong correlation and a high level of estimation accuracy using the independent variables. The standard error is 0.01038, and the Durbin-Watson (DW) statistic is 1.70, further confirming the equation's reliability. To ensure the validity of the equation and the absence of autocorrelation in the random errors of the independent variables, a residual analysis was conducted. It was found that the observations are randomly distributed, suggesting that the equation can be confidently used to estimate the current annual growth in height of *Pinus brutia* trees of varying ages in the forests of Dohuk. To visualize this relationship between the variables, a graph was prepared, as shown in Figure (3).

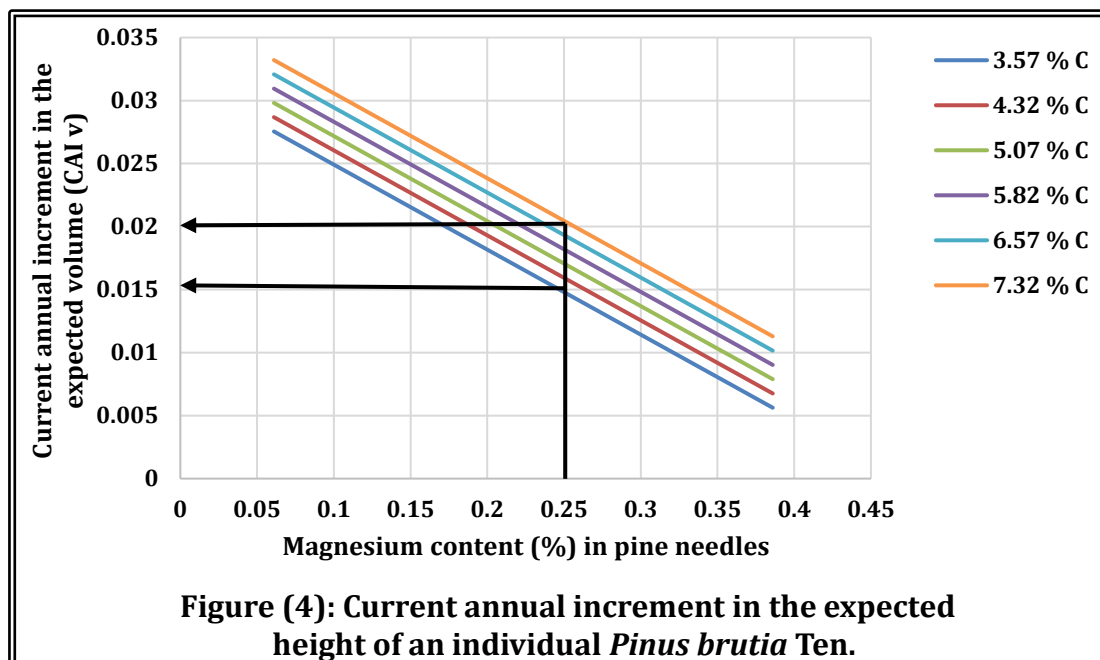


From Figure (3), we observe that an increase in the carbon content of the leaves leads to a higher current annual growth rate in height. Conversely, an increase in the magnesium content of the leaves results in a decrease in the current annual growth in height. When the magnesium content of the leaves is 0.2% and the carbon content is 3.57%, the current annual growth in height is 0.26 cm. However, when the carbon content increases to 7.32%, while maintaining the same magnesium concentration, the current annual growth rate in height is expected to increase to 0.3 cm for *Pinus brutia* trees of varying ages in the forests of Dohuk. Referring to Table (1), it is clear that equations (9, 10, 11, 12) are used to estimate the current annual growth in volume of *Pinus brutia* trees of unequal age growing in the forests of Dohuk. These estimates are based on the physiological characteristics, nutritional and mineral contents of the leaves, as well as the structural characteristics of the leaves in terms of thickness and leaf mass per unit area. The

statistical measures for these equations, represented by the coefficient of determination (R^2), are 97.85, 88.60, 93.27, and 93.76, respectively. The standard errors are 0.000914, 0.00199, 0.00145, and 0.00164, and the Durbin-Watson (DW) statistics are 1.75, 1.40, 1.77, and 1.71. Therefore, equation (9) provides the best estimate.

$$\text{CAI } v = 0.0262786 - 0.0674502 * \text{Mg} + 0.00151081 * \text{C}$$

The current annual growth in volume is estimated based on both the magnesium and carbon content of the leaves. The coefficient of determination (R^2) for this equation reached 97.85%, with a standard error of 0.000914 and a Durbin-Watson (DW) statistic of 1.75. These statistical measures indicate that the equation is well estimated and that the independent variables significantly affect the estimation of current annual growth in volume. To assess the reliability and validity of the equation and ensure there is no autocorrelation between the random errors of the independent variables, a residual analysis was conducted. The results showed a random distribution of observations around the zero point, confirming that the equation can be used to estimate the current annual growth in volume of *Pinus brutia* trees of varying ages in the forests of Dohuk. To further clarify this relationship between the variables, a graph was prepared, represented by a histogram, as shown in Figure (4).



From Figure (4), we observe that increasing the carbon content of the leaves leads to an increase in the current annual growth in volume, while an increase in the magnesium content results in a decrease in the current annual growth in volume of *Pinus brutia* trees. When the magnesium content of the leaves is 0.25% and the carbon content is 3.57%, the expected current annual growth in volume is 0.015 cm³. However, when the carbon content increases to 7.32%, while keeping the magnesium content constant, the current annual growth in volume is expected to increase to 0.02 cm³. It is evident from the equations chosen from Table (1) that the coefficient of determination (R^2) is significant. By relying on only two independent variables, we can estimate the growth functions (diameter, height, volume) of *Pinus brutia* trees in uneven-aged mixed forests in Dohuk. These equations rely on independent variables such as the carbon and magnesium content of the leaves, leaf thickness, and leaf mass per unit area, all of which influence the estimation of the annual growth functions. Increasing the leaf content has a positive effect on these functions because carbon is an essential element in photosynthesis and supports biological and physiological processes. As carbon increases, leaf gas exchange also increases, leading to higher metabolic rates, which in turn promotes the production of carbohydrates essential for cell division and the formation of plant tissues. This process enhances the energy supply for developing tissues in the roots, stems, branches, and leaves, and increases the trees'

resistance to various environmental stresses (Taylor and Clark, 2020). The negative effect of increased magnesium content in leaves on annual growth parameters is due to magnesium toxicity, which disrupts the nutritional balance within the trees. Excessive magnesium interferes with vital physiological processes such as photosynthesis and creates competition with other essential nutrients like calcium and potassium, which are crucial for growth and development. Magnesium plays an important role in synthesizing chlorophyll, which is vital for photosynthesis, but excess magnesium can impair chlorophyll synthesis and reduce photosynthetic efficiency. Additionally, high magnesium concentrations negatively affect enzyme activity, slowing down critical processes such as growth and respiration, ultimately stressing the tree's growth (Williams and Parker, 2021). On the other hand, leaf mass per unit area is positively associated with increased growth. The increased tissue density, including chloroplasts, allows the leaves to absorb more light, improving the efficiency of photosynthesis. As a result, carbohydrate production for growth and development increases. Additionally, greater leaf thickness and mass enhance the leaves' ability to survive longer periods, positively affecting photosynthesis. These thicker, denser leaves are more resilient to environmental stresses such as drought, humidity variations, and temperature fluctuations, thereby improving the trees' ability to thrive in harsh environmental conditions (Zhang and Li, 2020).

Conclusion

The study developed several mathematical models, graphs, and tables to estimate the relationship between the physiological characteristics of pine tree leaves and their impact on the current annual growth in diameter, height, and volume. It was found that leaf thickness, the total surface area of the tree crown, and the proportions of magnesium and carbon significantly influence the growth functions. These relationships were clearly demonstrated through multiple regression equations, which can be relied upon for accurate estimation.

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